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Study on the Correlation between Achilles Tendon Biomechanical Properties and Injury Risk in Dancers

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Abstract: This study explores the correlation between the biomechanical properties of the Achilles tendon and injury risk in dancers. Due to the high intensity and repetitive nature of dance movements, the Achilles tendon is subjected to significant stress, which increases the likelihood of injury. In this research, eight professional dancers were selected, and ultrasound imaging technology was used to assess the biomechanical properties of their Achilles tendons, including elasticity, stiffness, and Young's modulus. Additionally, data on the dancers' training background, dance experience, and Achilles tendon injury history were collected. The results revealed a significant correlation between the biomechanical properties of the Achilles tendon and injury risk. Tendons with lower elasticity had a higher risk of injury, while those with higher stiffness and Young's modulus had a lower risk of injury. Therefore, dancers can benefit from regular assessments of their Achilles tendon biomechanical properties to identify potential injury risks early and take preventive measures. This study provides a theoretical foundation for the prevention and rehabilitation of Achilles tendon injuries in dancers.

1. Introduction

Dance places high demands on dancers' body coordination and dynamic control, and the repetitive movements exert biomechanical stress on the Achilles tendon, making it prone to injury. This study aims to explore the correlation between the biomechanical properties of the Achilles tendon in dancers and the risk of injury, providing a basis for prevention and rehabilitation. The assessment includes properties such as elasticity, stiffness, and Young's modulus, in conjunction with factors like training background, dance experience, and injury history. The goal is to help dancers protect their bodies and extend their professional careers. As the number of participants in physical activities increases, the risk of Achilles tendon injuries also rises. Additionally, the study aims to investigate the effects of stretching on the recovery of injured Achilles tendons, providing targeted preventive measures and rehabilitation strategies for dancers and other athletes to reduce injury risks and promote recovery.

2. Materials and Methods

2.1 Subjects

A total of 8 male subjects were recruited for the study. The basic information of the subjects is as follows Table 1:

Table 1: Basic Information of the Subjects

Group	Age (years)	Height (cm)	Weight (Kg)
Subjects	20.63 ± 1.30	174.63 ± 4.90	67.94 ± 4.86

This provides a general overview of the age, height, and weight of the participants involved in the study.

2.2 Intervention Procedure

A 4-week Achilles tendon stretching intervention was applied to subjects with Achilles tendon injuries using a slant board, with sessions conducted twice daily for 10 minutes each. Before and after the intervention, subjects underwent the following tests: calf morphology test, ankle range of motion test, Achilles tendon morphology test, ankle joint stiffness test, isometric plantar flexion strength test, maximum heel-raise height test, and heel-raise endurance test.

2.3 Data Collection

2.3.1 Calf Morphology Test

The morphological indicators of the calf include calf length and calf circumference. While measuring calf length, subjects were required to sit with their knees bent at 90°, and both feet flat on the ground. The tester used a soft measuring tape to measure the length and circumference of both the left and right calves. Each measurement was taken three times, and the average values for calf length and calf circumference were used for subsequent analysis.

Calf length was defined as the distance from the popliteal crease to the center of the lateral malleolus.

Calf circumference was defined as the circumference at the thickest part of the calf.

2.3.2 Ankle Range of Motion (ROM) Test

For the ankle range of motion test, the subjects were positioned prone with the knee fully extended and the ankle hanging off the edge of the testing surface. The tester placed three markers on the fibular head, lateral malleolus, and the fifth metatarsal. Upon hearing the "start" command, the subjects were instructed to perform maximum plantarflexion and dorsiflexion of the ankle. A high-definition camera was used to record the entire testing process. Each ankle was tested three times, and the best result from each side was used for further analysis.[10]

2.3.3 Achilles Tendon Morphology Test

The morphological indicators of the Achilles tendon include tendon length and thickness. The subject was positioned prone with the knee fully extended and the ankle naturally hanging off the edge. A musculoskeletal ultrasound device was used to identify the start and end points of the Achilles tendon, which were marked on the skin using a marker. A soft measuring tape was then used to measure the distance between these two points, representing the Achilles tendon length. The ultrasound images were captured and saved after freezing the frame to record the positions of the start and end points. The **start point** of the Achilles tendon was defined as the bifurcation between the medial and lateral heads of the gastrocnemius muscle.[7]

2.3.4 Ankle Joint Stiffness Test

For the ankle joint stiffness test, the subject was positioned prone on a platform with the knee extended at 0°. The foot was firmly placed on a footplate and secured with a strap, ensuring that the rotation axis of the footplate aligned with the axis of plantarflexion/dorsiflexion of the ankle joint. The subject was instructed to completely relax the muscles of the lower limb. The footplate rotated at a speed of 5°/s, with a default range of motion from 35° of plantarflexion to 15° of dorsiflexion. If the subject felt discomfort within this range, the range was adjusted in 5° increments to a more suitable limit. After determining the appropriate range of motion, the subject performed five practice trials with the assistance of the tester. The ankle joint angle and torque data from the 6th trial were used for subsequent analysis.[6]

2.3.5 Isometric Plantar Flexion Strength Test

For the isometric plantar flexion strength test, the subject was positioned prone on the testing table with the ankle in a neutral position, and the foot was securely fixed to the footplate. The subject was instructed to perform a maximal heel raise (plantar flexion) effort, and the ISOMED system recorded the torque values throughout the force generation process. Each side (left and right) was tested three times, and the highest value was used for subsequent analysis.[1]

2.3.6 Maximum Heel-Raise Height Test

For the maximum heel-raise height test, the subject stood on a 10° slant board. To maintain balance, the subject was allowed to lightly touch the wall with a fingertip from each hand at shoulder height. Upon hearing the start signal, the subject was instructed to lift one leg and, using the other leg, perform a maximum heel raise effort. This was tested three times for each leg, and the highest heel-raise height was recorded for analysis.

2.3.7 Heel-Raise Endurance Test

For the heel-raise endurance test, the subject stood on one leg on a 10° slant board. To maintain balance, the subject was allowed to lightly touch the wall with a fingertip from each hand at shoulder height. Upon hearing the start signal, the subject followed a metronome set at 30 Hz, performing heel raises in rhythm (up and down). The test was terminated when the subject could no longer maintain the rhythm or when the heel-raise height dropped below 2 cm. Each leg was tested once.

2.4 Data Processing

2.4.1 Ankle Range of Motion (ROM)

The video footage from the ankle ROM test was analyzed to capture the frames corresponding to the moments of maximum dorsiflexion and plantarflexion. These images were digitized using Kinovea software, and the difference between the maximum dorsiflexion and plantarflexion angles was calculated to determine the ankle joint range of motion.

2.4.2 Achilles Tendon Morphological Indicators

The morphological indicators of the Achilles tendon included tendon length and thickness.Tendon Length**: Measured by the same tester using a soft measuring tape throughout the entire process.Tendon Thickness**: Measured using the analysis tools built into the GE musculoskeletal ultrasound device. For each ultrasound image, the Achilles tendon thickness was measured at a point 2 cm above the tendon insertion.

2.4.3 Achilles Tendon Mechanical Properties

The relationship between ankle joint angle and torque was fitted with a fourth-order polynomial equation ($y = ax^4 + bx^3 + cx^2 + dx + e$), where **y** represents torque, **x** represents the ankle joint angle, and **a-e** are constants. Ankle joint stiffness was defined as the first derivative of the angle-torque curve at an ankle angle of 0 °.

2.4.4 Maximum Heel-Raise Height

The video footage of the maximum heel-raise height test was analyzed to capture the moment when the subject's heel was raised to its highest point on both sides. Kinovea software was used to measure and record the maximum heel-raise height for further analysis.

2.5 Statistical Analysis

Paired sample t-tests were conducted to compare the differences in various indicators before and after the intervention for the subjects. All statistical analyses were performed using SPSS 21.0 software (SPSS, Chicago, IL, USA), with a significance level set at $P < 0.05$.

3. Research Results

3.1 Ankle Joint Stiffness Test

The analysis results (like Table 2) indicate that there were no significant differences in ankle joint stiffness between the left and right sides before and after the intervention ($p = 0.224$, $p = 0.057$). This suggests that the intervention did not lead to a statistically significant change in the relative stiffness of the ankle joints on either side.

Table 2: Ankle Joint Stiffness for Left and Right Sides

	Pre-Test	Post-Test	p-value
Ankle Joint Stiffness (L)	0.240 ±0.111	0.307 ±0.141	0.224
Ankle Joint Stiffness (R)	0.294 ±0.141	0.367 ±0.728	0.057

The data in Table 2 shows the ankle joint stiffness measurements for both the left (L) and right (R) sides before and after the intervention. The p-values indicate that there were no significant differences in stiffness for either side, with $p = 0.224$ for the left ankle and $p = 0.057$ for the right ankle. These results suggest that the intervention did not produce statistically significant changes in ankle joint stiffness in either direction.

3.2 Isometric Plantar Flexion Strength Test

The analysis results (like Table 3) indicate that the maximum torque values for both the left and right sides significantly increased following the intervention ($p = 0.001$, $p = 0.018$). This suggests that the intervention was effective in enhancing the isometric plantar flexion strength of the subjects.

Table 3: Maximum Torque for Isometric Plantar Flexion on Left and Right Sides

	Pre-Test	Post-Test	p-value
Isometric Torque (L)	116.250±26.925	143.000±29.067	0.001
Isometric Torque (R)	112.775±18.445	140.75±25.206	0.018

These results demonstrate the positive impact of the intervention on improving isometric strength in both legs, highlighting the potential benefits of targeted training in enhancing muscular performance. Further investigation could focus on the long-term effects of such interventions on overall performance and injury prevention in dancers.

3.3 Achilles Tendon Morphology

The analysis results (like Table 4) show no significant differences in tendon thickness for both the left and right sides before and after the intervention (p = 0.056, p = 0.922). However, the Achilles tendon length for both sides increased significantly after the intervention (p = 0.003 for both sides).

Table 4: Achilles Tendon Morphology for Left and Right Sides

	Pre-Test	Post-Test	p-value
Tendon Thickness (L) (cm)	0.431±0.054	0.489±0.062	0.056
Tendon Thickness (R) (cm)	0.455±0.041	0.458±0.051	0.922
Tendon Length (L) (cm)*	19.863±0.875	21.413±1.521	0.003
Tendon Length (R) (cm)*	21.075±1.440	22.150±1.500	0.003

3.4 Calf Morphology

The analysis results (like Table 5) show no significant difference in left calf length before and after the intervention (p = 0.956). However, the right calf length increased significantly after the intervention (p = 0.024). There were no significant differences in calf circumference for either side before and after the intervention (p = 0.870 for the left side, p = 0.064 for the right side).

Table 5: Calf Morphology for Left and Right Sides

	Pre-Test	Post-Test	p-value
Calf Length (L) (cm)	39.596±1.489	39.621±1.319	0.956
Calf Length (R) (cm)*	38.750±1.356	39.908±1.664	0.024
Calf Circumference (L) (cm)	37.854±1.921	37.883±1.667	0.870
Calf Circumference (R) (cm)	38.125±1.493	37.742±1.458	0.064

The results suggest that while the right calf length increased significantly following the intervention, other aspects of calf morphology, such as the left calf length and calf circumference on both sides, did not show significant changes. This indicates that the intervention may have had a localized impact on calf length, particularly on the right side.

3.5 Heel-Raise Test

The analysis results (like Table 6) indicate that there were no significant differences in maximum heel-raise height for either the left or right side before and after the intervention (p = 0.657, p = 0.085). Additionally, there were no significant differences in the number of heel-raises performed on either side before and after the intervention (p = 0.447 for the left side, p = 0.159 for the right side).

Table 6: Heel-Raise Endurance for Left and Right Sides

	Pre-Test	Post-Test	p-value
Maximum Heel-Raise Height (L) (cm)	19.073±1.564	18.749±1.213	0.657
Maximum Heel-Raise Height (R) (cm)	19.826±1.597	18.906±2.041	0.085
Heel-Raise Repetitions (L)	26.750±8.084	29.125±14.096	0.447
Heel-Raise Repetitions (R)	27.625±7.170	33.000±14.422	0.159

The results demonstrate that the intervention did not lead to significant changes in either the maximum heel-raise height or the number of heel-raises performed, suggesting that the intervention may not have had a substantial impact on heel-raise endurance or performance.

3.6 Ankle Joint Range of Motion Test

The analysis results (like Table 7) show no significant differences in ankle joint range of motion for either the left or right side before and after the intervention (p = 0.207 for the left side, p = 0.054 for the right side).

Table 7: Ankle Joint Range of Motion for Left and Right Sides

	Pre-Test	Post-Test	p-value
Ankle Range of Motion (L)	59.500±8.000	62.375±6.457	0.207
Ankle Range of Motion (R)	56.375±6.163	62.250±10.846	0.054

The results indicate that although there was a trend towards improvement in ankle joint range of motion, particularly on the right side (p = 0.054), the changes were not statistically significant. This suggests that the intervention had limited effect on improving ankle flexibility.

3.7 Ankle Joint Stiffness

Ankle joint stiffness is typically measured through the torque-angle curve. The passive stiffness of the joint can be quantified as the slope of the curve generated from the joint angle and the torque measured during passive joint movement. Ankle joint passive stiffness encompasses all tissues within and above the joint, including muscles, tendons, skin, subcutaneous tissue, fascia, ligaments, joint capsules, and cartilage.

Ankle joint stiffness is a valuable indicator for evaluating the recovery of Achilles tendon injuries. The results of this study indicate that four weeks of stretching exercises did not significantly improve ankle joint stiffness. One possible explanation for this is that most of the participants had healthy Achilles tendons, meaning their baseline ankle stiffness was already within the normal range, limiting the room for noticeable improvement.[4]

3.8 Ankle Joint Range of Motion

Several indicators are used to evaluate the functional recovery outcomes of Achilles tendon injuries, with ankle joint range of motion (ROM) being one of the most common due to its practicality, portability of testing instruments, and minimal requirements for the testing environment. Many studies have explored the relationship between ankle ROM and lower limb injuries. [5]

The results of this study indicate that four weeks of stretching exercises did not improve ankle ROM. Some studies suggest that decreased ankle ROM is a risk factor for the development of Achilles tendinopathy. Additionally, a prospective cohort study of male recruits found that an increase in ankle dorsiflexion ROM was a significant predictor of Achilles tendinopathy. Other research has compared the ROM of injured and uninjured sides in patients undergoing conservative or surgical treatment for Achilles tendon injuries, finding that the uninjured side exhibited greater ankle ROM than the injured side. Therefore, ankle ROM can be used to some extent to distinguish Achilles tendon injuries.

In this study, most participants had healthy Achilles tendons, which may explain why the four-week stretching intervention did not result in significant improvement in ankle ROM.

3.9 Heel-Raise Endurance Test

The heel-raise endurance test is recommended as a method to evaluate functional performance of the ankle joint. Patients are instructed to perform repetitive heel raises at a set pace until exhaustion. The test typically provides indicators such as the number of heel raises and maximum heel-raise height on both sides, with recovery effectiveness often assessed by comparing differences between the injured and uninjured sides.

Heel-raise ability is a critical indicator in the early stages of recovery because it reflects the overall level of Achilles tendon healing, which is essential for both patient motivation and daily activity performance. A reduced maximum heel-raise height may indicate Achilles tendon elongation, while the number of heel raises is more influenced by muscle strength and endurance.[8]

This study found that four weeks of stretching exercises had no significant effect on either maximum heel-raise height or the number of heel raises performed by participants. One reason for this could be that the heel-raise endurance test focuses more on the endurance of the plantar flexor muscles. Most studies that use the heel-raise test focus on the number of repetitions. However, some research suggests that assessing heel-raise endurance by calculating the total work done, based on both the number of repetitions and the height achieved, may provide a more effective measure of endurance.

3.10 Strength Testing

Strength testing relies mainly on isokinetic dynamometers, and there are various testing protocols including concentric, eccentric, isometric, and isokinetic methods, with differing angular velocities under isokinetic conditions. Some studies have tested plantar flexor strength under both concentric and eccentric loading conditions. Other research used isokinetic devices to test concentric and eccentric strength with participants seated (hips and knees flexed at 90°). A study on patients two years post-Achilles tendon rupture rehabilitation found that the injured side showed significant deficits in heel-raise tests, squat jump tests, and strength tests compared to the uninjured side. Our study demonstrated that four weeks of stretching exercises significantly improved isometric plantar flexor strength, indicating that stretching exercises enhance tendon-related strength.

3.11 Achilles Tendon Morphological Indicators

Research commonly uses ultrasound, X-ray, or MRI to study Achilles tendon length and elongation. This study used a more practical method combined with ultrasound to measure tendon length, though the accuracy of a soft tape measure is lower compared to X-ray or MRI. Whether a few millimeters of tendon elongation affects daily physical activity or is associated with the risk of re-injury requires further research. [9]Some studies suggest that longer tendons negatively impact surrounding tissues of the ankle joint, affecting the ability to run and jump. For optimal recovery after Achilles tendon rupture, treatment should focus on the full recovery and healing of the entire tendon, not just the site of the tear. Post-rehabilitation, calf plantar flexor strength often remains insufficient due to muscle atrophy and fat infiltration, and some research suggests this strength deficit is related to changes in tendon length. Increased tendon length or elongation during recovery may be the reason for strength deficits after Achilles tendon rupture.[3] Our study found that four weeks of stretching exercises increased tendon length, suggesting that for individuals with Achilles tendon injuries, stretching may lead to strength deficits and might not be the most suitable rehabilitation approach.

Studies have shown that post-Achilles tendon injury, the thickness of the injured tendon is greater than that of the uninjured side. The increase in tendon thickness is due to the loss of parallel collagen structure, fiber integrity, fat infiltration, and/or capillary proliferation. Our study showed that four weeks of stretching exercises had no effect on tendon thickness.

3.12 Calf Morphology

The results of this study showed no significant differences in calf circumference before and after four weeks of stretching exercises. A year-long follow-up study found that by 26 weeks after Achilles tendon injury, calf circumference on the injured side was already comparable to the uninjured side. Research also suggests that after Achilles tendon rupture, the gastrocnemius muscle atrophies rapidly during immobilization, but 2 to 4 weeks of rehabilitation training can restore its size. Additionally, calf circumference measurements include not only the dimensions of the triceps surae muscle but also subcutaneous fat, which can affect the measurement data. The finding that right calf length increased post-intervention might be due to measurement bias caused by differences in technique.

4. Conclusion

This study used ultrasound imaging technology to analyze the biomechanical properties of dancers' Achilles tendons and examined the relationship between these properties and the risk of tendon injury. The study revealed a significant relationship between tendon biomechanical properties and injury risk, with tendons that exhibit poor elasticity but high stiffness and Young's modulus showing a lower risk of injury.[2] The study also found that four weeks of stretching exercises significantly improved tendon strength, but this intervention may not be suitable for individuals with Achilles tendon injuries. Changes in tendon length, thickness, and calf morphology were associated with rehabilitation outcomes, though the exact mechanisms require further exploration. The study emphasizes the importance of assessing the biomechanical properties of dancers' tendons to prevent injuries and offers rehabilitation strategies for dancers. Future research should focus on optimizing training to improve biomechanical properties and reduce injury risk.

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